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Jay C. Hardin
NASA Langley Research Center

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Computational Aeroacoustics Applied to Active Noise Control

Jay C. Hardin
NASA Langley Research Center

ABSTRACT

Computational Aeroacoustics (CAA) is a rapidly developing new technology that allows computation of the generation and propagation of sound from first principle governing equations. This paper discusses the application of this technique to environmental noise control, such as in the interior of a space station. In particular, sound generation by vibrating structures; fans in ducts; and active noise control, where either a secondary sound field is introduced to cancel an unwanted sound field or temporal techniques are employed to reduce the source intensity itself, are included.

INTRODUCTION

Noise control always implies a good understanding of the source to be controlled. Whether the control is achieved by reducing the intensity of the source or by generating a secondary source that acts to partially cancel the unwanted source, success depends on a fundamental understanding of the source characteristics. Unfortunately, in the past, such information was usually lacking since the source often depended on fluid dynamics, which could neither be measured nor calculated. Thus, sources were modeled, a technique which was not sufficiently accurate for noise control.

Recently, the field of computational aeroacoustics has been under development. This approach calculates the time-dependent flow, which contains all the source dynamics necessary to understand and reduce the source, from the fundamental governing equations. Of course, such four-dimensional calculations are computationally intensive, and one cannot perform acoustic design studies on their favorite computer yet. However, the physical insights gained from those solutions that have and can be obtained have a variety of applications.

APPLICATION OF CAA

The sources of sound that occur in nature can be understood by rewriting the governing compressible Navier-Stokes equations as

$$\Box^2 p = \frac{\partial \dot{m}}{\partial t} - \frac{\partial F_i}{\partial x_i} + \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$$

where $\Box^2 p$ is the linear wave operator operating on the pressure p, $\dot{m}$ is the rate of mass addition to the region of interest, F_i are the components of any forces per unit volume acting on the fluid medium, and T_{ij} is the Lighthill stress tensor.[1]

The terms on the right hand side of this equation are the sources of sound that, with one exception, depend on the dynamics of the flow. The one exception occurs when a surface is caused to vibrate

by some external means. The vibration of the surface exerts a time-dependent force on the medium that acts as a source of sound. Such radiation is quite straightforward to determine by CAA techniques when the vibration of the surface is known. For example, Figure 1 displays the sound field radiated by a piston in a baffle oscillating at different frequencies. The light patterns are compressions where the density is higher than the ambient, while the dark patterns are rarefications where the density is lower than ambient. This source is undoubtedly responsible for the failure of the refrigerators and freezers that have flown on the Shuttle to meet the noise requirement of producing sound spectra whose levels lie below the NC40 curve. The noise control technique for such sources is also simple--stop the vibration. This can be accomplished through standard design techniques or, more recently, by active vibration control utilizing piezoelectric transducers which are discussed below.

The other acoustic sources are generated by the flow of a fluid. The first of these, $\frac{\partial \dot{m}}{\partial t}$, says that if mass is added to the region of interest at a variable rate, sound is produced. Thus, a steady turbulent jet flow, which adds mass at a constant rate, would not make sound by this mechanism (although it will by another), while it is responsible for sound generation by an automobile exhaust, where mass is added at a variable rate. This type of source is called a monopole, because it tends to radiate in a spherically symmetric fashion and is the most efficient way to create sound, yielding mean square pressure proportional to MV^3, where M is the Mach number and V is the characteristic velocity of the flow. This is most likely the source responsible for the difficulty in meeting the NC40 curves within the International Space Station Alpha, while still providing intermodule ventilation to meet required oxygen and carbon dioxide partial pressures. For noise control, if mass must be added to a region, say through a valve, it should be done as steadily and at as low a velocity as possible.

The second source term, $\frac{\partial F_i}{\partial x_i}$, says that force gradients acting on a fluid will generate noise if they are time dependent. Time dependency is necessary since a steady solution will not be perceived as sound (i.e., the ear is only sensitive to frequencies in the range of 50Hz-20KHz, with peak sensitivity near 1-2KHz). This type of source is called a dipole since it is equivalent to two monopoles 180° out of phase (i.e., one is condensing the gas while the other is rarefying it), slightly displaced from one another in the direction of the gradient. Since these two monopoles are essentially working against one another, the mean square pressure radiated is less than that for a monopole, at least for subsonic flows, being proportional to M^3V^3, and its radiation or directivity pattern is that of a figure eight.

As an example of the application of CAA to such sources, Figure 2 depicts the sound field radiated by a cylinder in a uniform flow. Here, the wake of the cylinder consists of a von Karman vortex street where vortices are alternately shed from the upper and lower surfaces of the cylinder. As each vortex is shed, it exerts a force on the cylinder that, since it cannot move, exerts a force back on the fluid by Newton's law. It is this force acting on the fluid that leads to the generation of sound seen in Figure 2 as light colored compressions and dark colored rarefications. A second example is shown in Figure 3, which is a CAA calculation of sound generated by flow over a cavity in a

surface.[2] Such calculations are often done in two parts so that optimum numerical schemes and grids can be utilized for both the viscous and acoustic aspects of the problem. Figure 3a depicts vorticity contours within the flowfield at a particular instant of time. In such a geometry, a large vortex is trapped within the cavity, which alternately drags the shear layer into the cavity and then expels it into the wake. This periodic oscillation leads to the radiation of sound as shown in the temporal sequence of plots in Figure 3b. Note that the acoustic grid of Figure 3b is much higher than the flow grid of Figure 3a. This is due to the fact that the wavelength of the sound produced, λ, is typically on the order of $\lambda \simeq L/M$, where L is a characteristic length of the flow. Thus, for subsonic flows, the wavelength is longer than the characteristic length. Source calculations, as well as the radiation pattern shown in Figure 3b, indicate that sound is primarily produced at the downstream end of the cavity. A CAA study of passive means for control of this source was carried out by Chokani and Kim.[3]

The most common example of this source in space station applications is probably due to the force exerted on the medium by moving blades, such as in a cooling fan. Much research has been carried out on this source, and good predictive capability is available.[4] For example, Figure 4 shows excellent comparison between measured and predicted noise levels radiated by a fan in a duct. Here, an aerodynamic code was used to predict the pressures on the blades, which then became the source terms fed into the acoustic code. Although most of this work has been done with high-speed aeronautical applications in mind, the technology is available for heating, ventilation, and air conditioning (HVAC) applications as well, such as would occur in a space station. In fans, the maximum velocity and, hence, major noise generation occurs near the tips of the blades. This tip velocity is proportional to the rpm of the rotor times the radius of the blades, and noise may be reduced by reducing either of these parameters. Changes in blade design or fan ducts (i.e. assuring uniform inflow to the fan and attached flow on the blades), that make the blade loading more steady may also be highly beneficial.

The final source term, $\frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$, is the true aeroacoustic source and is responsible for sound radiation by steady turbulent jet flows and boundary layers over flat surfaces. However, it is much weaker, corresponding to four monopoles or two dipoles working against one another and radiates mean square pressure proportional to M^5V^3. As it would not be expected to be very important in the essentially ambient atmosphere of a space station, it will not be discussed here.

ACTIVE NOISE CONTROL

Active noise control often embodies the idea of introducing a secondary sound field to partially cancel out an unwanted primary source. This concept is not as far fetched as it may sound since, as was discussed earlier, a dipole is nothing more than two competing monopoles. However, the phase relation is critical-- two monopoles in phase act like a monopole of twice the strength. Thus, it is important to precisely understand the source one is trying to cancel. This is why most applications thus far have been to periodic sources where the incoming signal could be predicted. Further, it is impossible to cancel the source completely over a finite region. This fact

may become important in an essentially reverberant environment such as a space station. However, the technology is gradually becoming more robust, and applications to broadband, random sources are achieving some success.

As an example of the application of CAA to active noise control[5], Figure 5 presents the calculation of flow over a curved surface. Figure 5a displays the surface and the computational domain. After uniform flow was established over this surface, a small wave packet was introduced upstream. Figure 5b is a temporal sequence of total vorticity contours as the wave packet traversed the curved surface. Note that the vorticity is amplified by passing over the curvature. This amplification leads to the production of sound. In Figure 6, the active control of this sound is depicted. Figure 6a presents the controller, which consists of a pair of pressure detectors, an adaptive filter and a control source. In Figure 6b, the directivity pattern of the sound radiation with and without control is presented. Note the approximately 6dB reduction in the peak radiation direction and significant reductions in other directions.

A CAA study of perhaps more relevance to space station applications was carried out by Lester and Lefebvre.[6] They evaluated the application of piezoelectric actuators for control of sound fields in cylinders. These actuators apply a bending moment to thin panels, such as trim panels in an aircraft, which causes them to act as loud speakers producing the controlling sound field. Subsequent tests confirmed predicted noise reductions in the range 11-14dB at acoustic resonance inside a cylinder through the use of only two such actuators and four monitoring microphones.

Active noise control may also involve attempts to actively control the sound sources themselves. One such application was reported by Hardin and Pope[7] who utilized CAA techniques to show that by rotation of, or suction through, a cylinder in a uniform flow, the formation of the Von Karman vortex street discussed earlier could be affected, resulting in elimination of the Aeolian tone noise radiation. Streamline patterns in these two cases are shown in Figure 7. A similar technique has been demonstrated experimentally by Ffowcs Williams and Zhao.[8]

CONCLUSION

This paper has discussed the application of computational aeroacoustics (CAA) to the control of noise sources. This new technology allows both the generation and propagation of sound to be calculated from first principles. Although CAA is computationally intensive, it allows:

1. The sources to evolve naturally from the fluid dynamics rather than be modeled. The additional understanding developed in this way is invaluable for noise reduction efforts.

2. Precise prediction of acoustic radiation from vibrating surfaces, rotating blades, and ducted fans.

3. Coupling with active noise control schemes to provide better source definition and an ultimate design capability on a computer.

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PISTON IN AN INFINITE BAFFLE

Density Contours

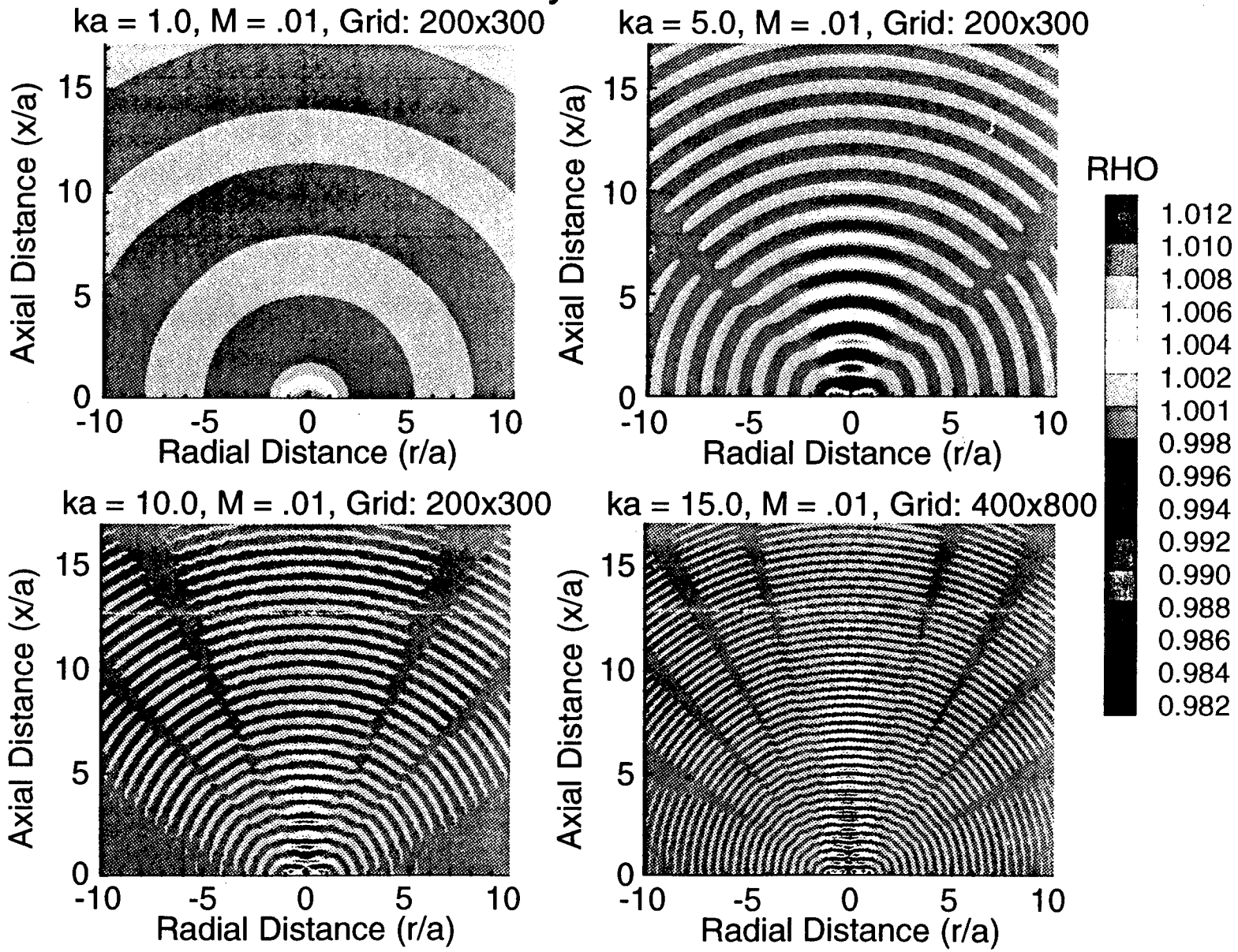


Figure 1: Radiation Patterns Produced by Baffled Piston

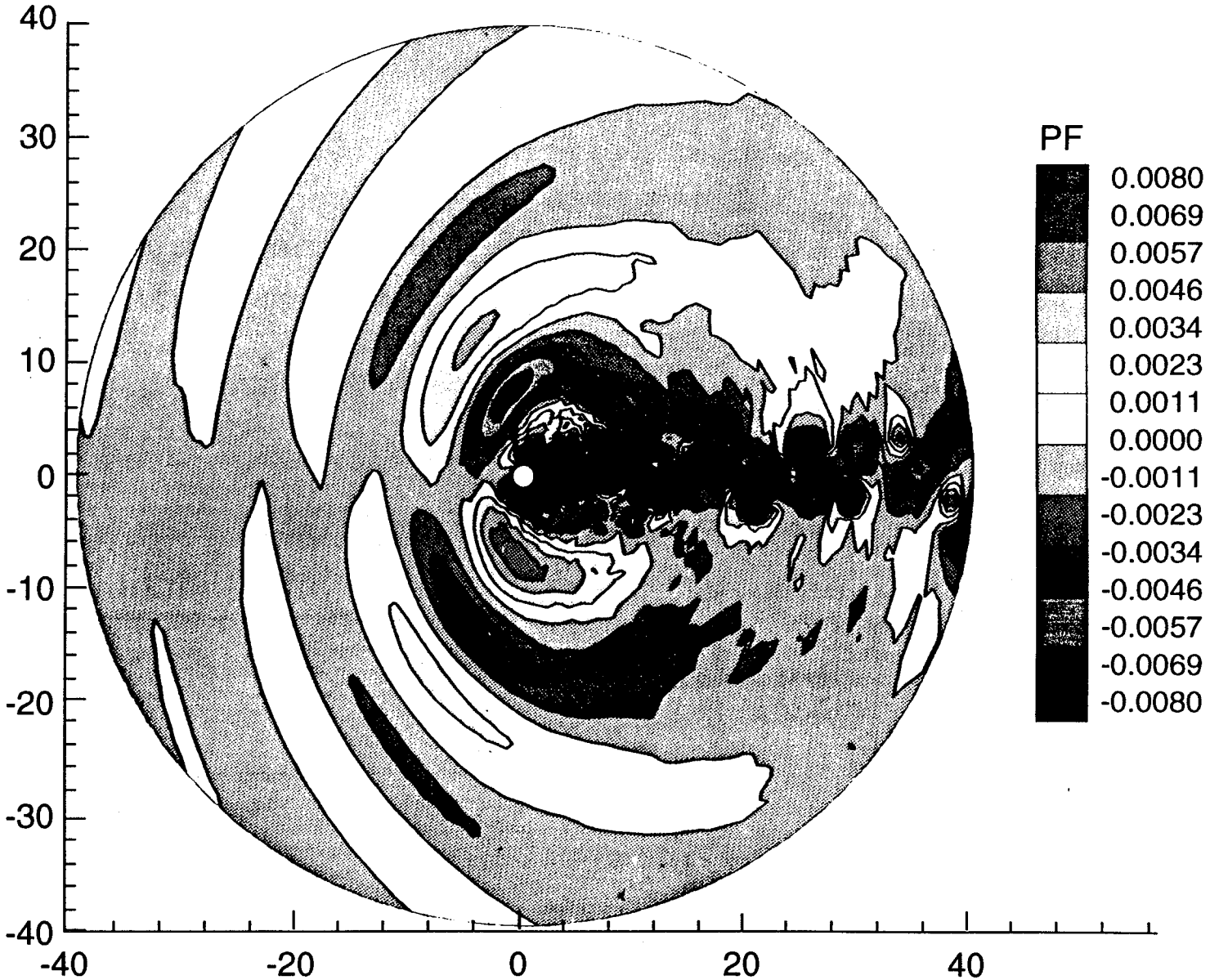


Figure 2: Sound Generation by a Cylinder in a Uniform Flow

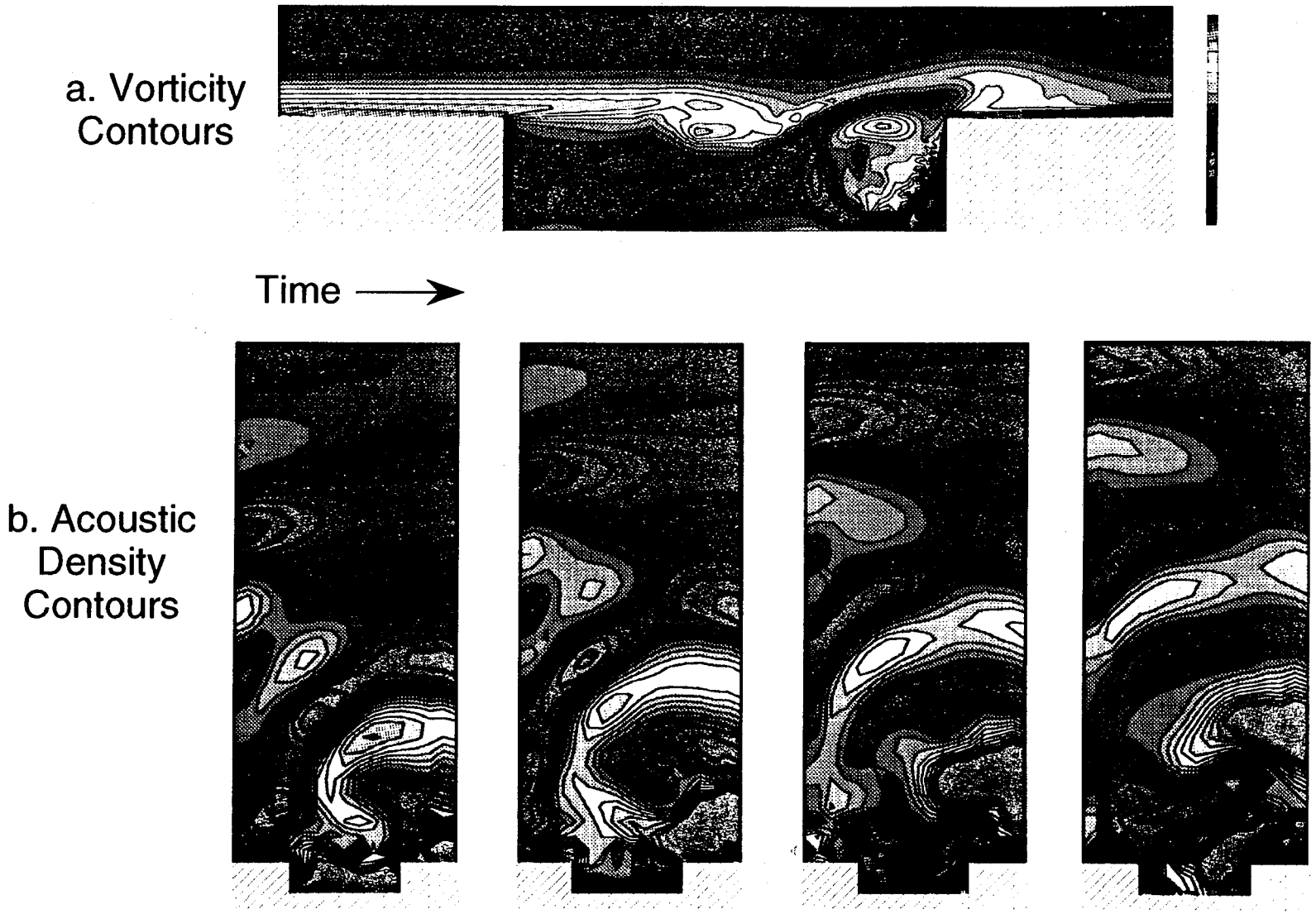


Figure 3: Sound Generation by Flow Over a Two Dimensional Cavity

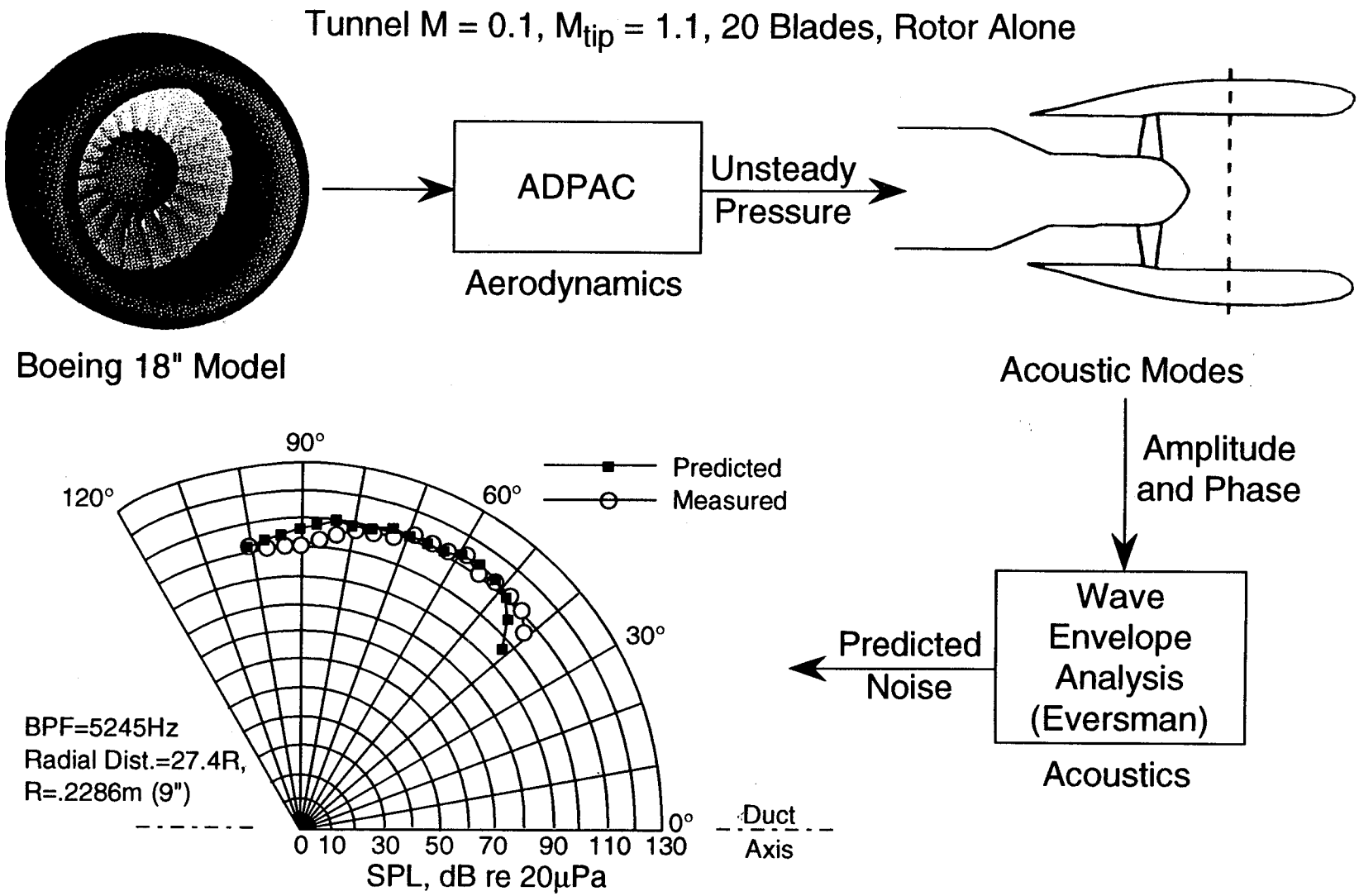
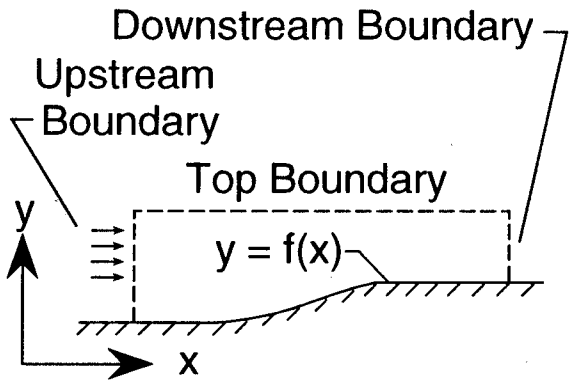
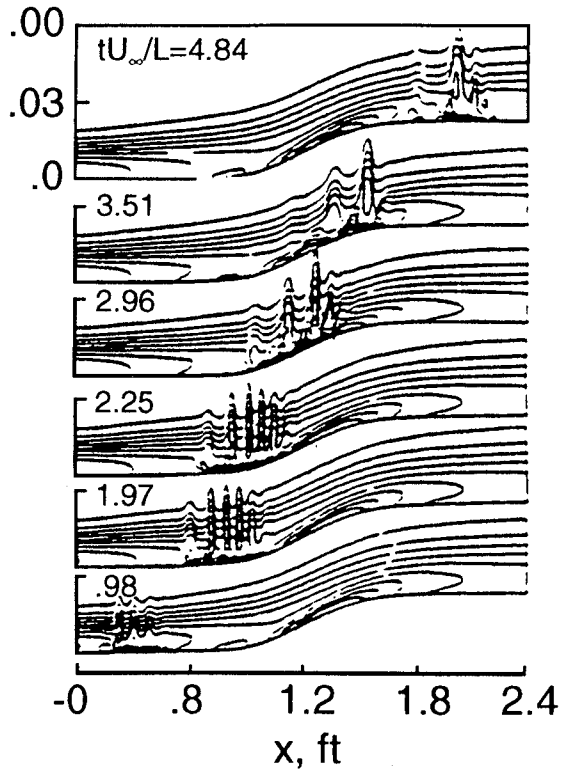


Figure 4: Ducted Fan Noise Prediction Based on Aerodynamic-Acoustic Coupling

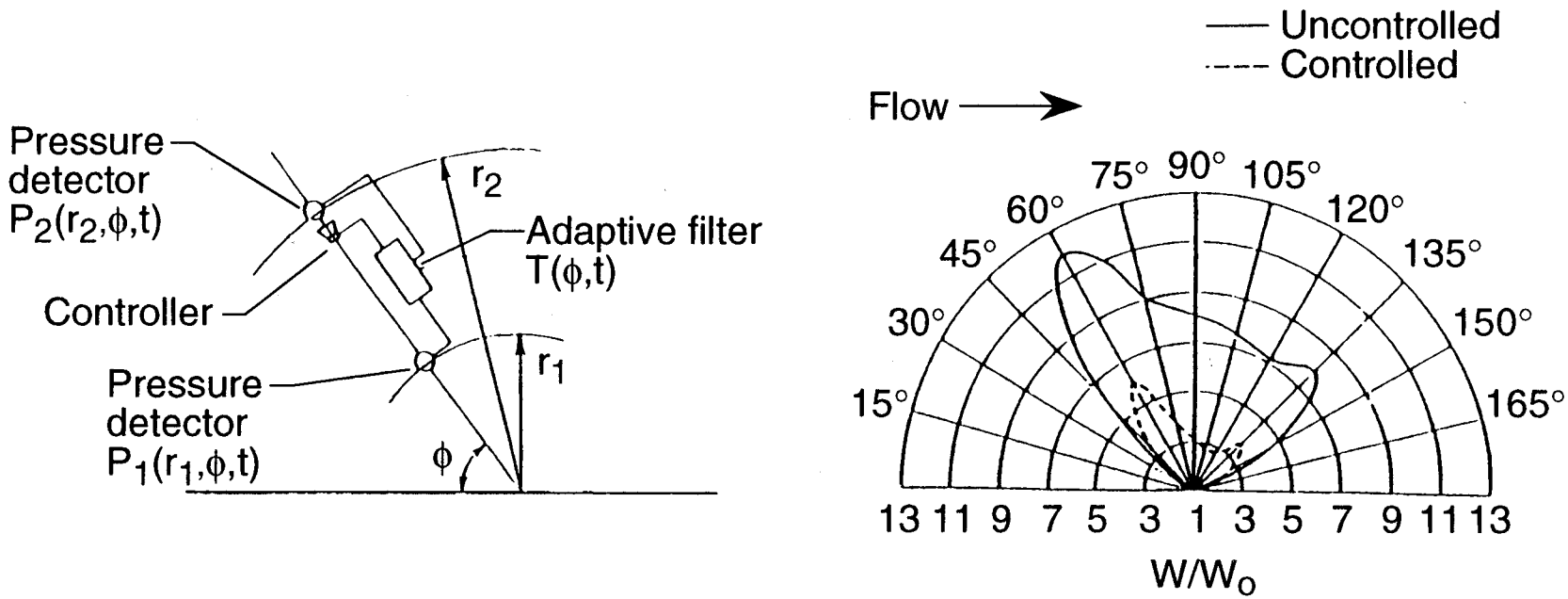


a. Schematic of the surface geometry and computational domain



b. Instantaneous total vorticity

Figure 5: Instability Wave Over Concave-convex Surface



a. Schematic of the sound control system.

b. Uncontrolled and controlled acoustic intensity at an 11-ft radius.

Figure 6: Active control of Sound Radiation

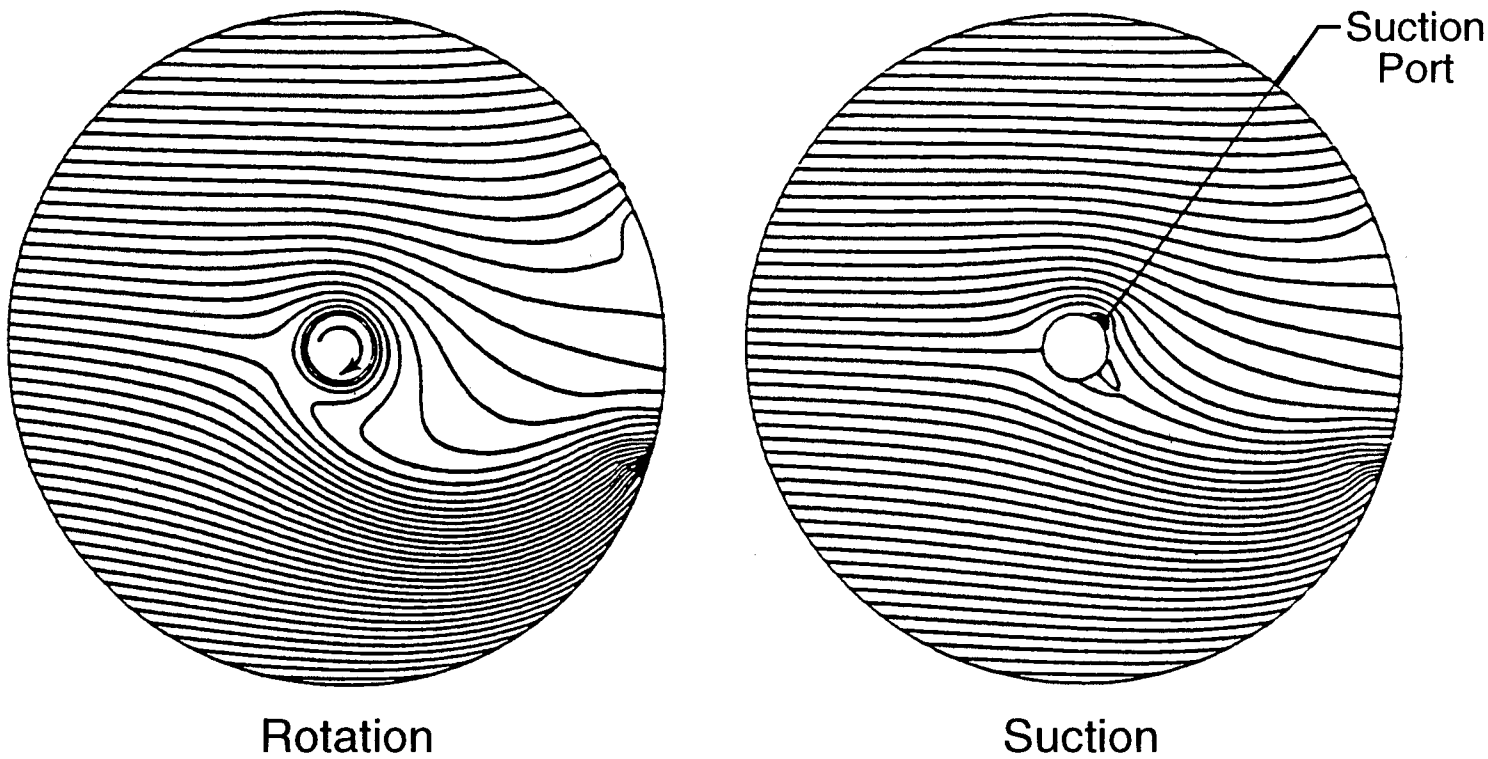


Figure 7: Comparison of Streamline Fields Produced by Constant Rotation and Internal Suction